# DESIGN PRINCIPLES FOR HIGH CURRENT BEAM INJECTION LINES

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We discuss the design principles for high current injection beam lines having a high degree of beam quality preservation. These principles are applied to designing a high current e-beam injection line delivering 10 MeV e-beams from the injector to an accelerator driving UV FELs, as proposed at CEBAF.

## I. INTRODUCTION

A 200 MeV recirculating SRF e-beam accelerator is being designed at CEBAF for driving kW-level industrial UV FELs [1, 2]. This accelerator, like all the FEL drivers, should provide e-beams having the smallest possible emittances. This demands minimization of the emittance growth at all of the stages of beam creation, acceleration and transport. One of the most critical regions is the injection line which transports the e-beams from a CW high current 10 MeV injector [3] to the accelerator.

It is interesting to consider in general how a high current injection beam line should be designed to provide a high degree of beam quality preservation, while providing the required matching conditions into the accelerator. For a non-circulating accelerator, one can minimize the emittance growth in the bending system by minimizing the average beam size [5], and match the beam into the accelerator by adding quadrupoles after the last dipole of the beam bending line. However, this prescription does not apply to a circulating accelerator, since the quads added between the last dipole and the accelerator disturbs the lattice for high-pass accelerated beams [6]. Alternative prescriptions must be sought for the latter case.

## II. GENERAL DESIGN PRINCIPLES

The first general principle that an injection line design should follow is symmetry. A symmetric bending system preserves the beam emittance better than an asymmetric bending system. since the symmetry minimizes the aberrations. Also, a symmetric achromatic system is more compact, since an asymmetric system requires more elements and more length to become achromatic.

Secondly, the beam should be bent gently. The bending angle is often limited by the given footprint or space to clear the high-pass accelerated beams from the injected beams. A rule-of-thumb has been given in [7] that the magnitude of the deflection of the injected beam should be less than $3° \times (W_1/W_0)$, where $W_1$ and $W_0$ are the energies of the first orbit and the injected beams respectively. This ratio is generally less than 10, so the maximum magnitude of the deflection of the injected beam should be less than $30°$ for a circulating accelerator.

Thirdly, the length of an injection line should be minimized. Therefore, a minimum number of magnets constituting an achromatic system should be used. One can use a single $\alpha$-magnet [8] or two conventional dipoles with a quad in between to constitute an achromatic bending sys-

tem. However, for more flexible beam matching and axial bunching, at least three dipoles are needed.

Fourth, the beam line should retain a high degree of flexibility in matching so that neither injector beams nor main accelerator beams are required to meet precise specifications in order to function.

## III. EMITTANCE GROWTH

Beam emittance growth in bends has been studied in detail in [9]. The responsible mechanisms were attributed to the anomalous noninertial transverse space-charge force and the normal longitudinal space-charge force. Useful formulas have been given for estimating the emittance growth from these two mechanisms.

In some earlier particle simulations of high current beam transport through an injection line [4], we turned the transverse and axial space charge forces on and off alternatively, and identified the axial space charge force as the cause of the emittance growth. The underlying mechanism is that the momentum of each electron is modified by the axial space charge force. and the beam ends up with a residual dispersion or emittance growth.

We now derive the beam emittance growth in the bending plane defined by the transfer matrix

$$
R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ 0 & 0 & \delta \end{bmatrix}, \qquad (1)
$$

where $\delta = 1$ is introduced to account for the momentum variation. Due to $\sigma(B) = R\sigma(A)R^T$. we have

$$
\begin{aligned}
\sigma_{11}(B) = {}& R_{11}^2 \sigma_{11}(A) + 2R_{11}R_{12}\sigma_{12}(A) \\
& + 2R_{11}R_{13}\sigma_{13}(A) + R_{12}^2\sigma_{22}(A) \\
& + 2R_{12}R_{13}\sigma_{23}(A) + R_{13}^2\sigma_{33}(A) \ , \ (2.1)
\end{aligned}
$$

$$
\begin{aligned}
\sigma_{12}(B) = {}& R_{11}R_{21}\sigma_{11}(A) + (R_{11}R_{22} + R_{12}R_{21})\sigma_{12}(A) \\
& + (R_{11}R_{23} + R_{13}R_{21})\sigma_{13}(A) + R_{12}R_{22}\sigma_{22}(A) \\
& + (R_{12}R_{23} + R_{13}R_{22})\sigma_{23}(A) + R_{13}R_{23}\sigma_{33}(A), \ (2.2)
\end{aligned}
$$

$$
\begin{aligned}
\sigma_{22}(B) = {}& R_{21}^2\sigma_{11}(A) + 2R_{21}R_{22}\sigma_{12}(A) \\
& + 2R_{23}R_{21}\sigma_{13}(A) + R_{22}^2\sigma_{22}(A) + 2R_{22}R_{23}\sigma_{23}(A) \\
& + R_{23}^2\sigma_{33}(A) \ , \qquad (2.3)
\end{aligned}
$$

$$
\sigma_{13}(B) = [R_{11}\sigma_{13}(A) + R_{12}\sigma_{23}(A) + R_{13}\sigma_{33}(A)]\delta, \ (2.4)
$$

$$
\sigma_{23}(B) = [R_{21}\sigma_{13}(A) + R_{22}\sigma_{23}(A) + R_{23}\sigma_{33}(A)]\delta, \ (2.5)
$$

$$
\sigma_{33}(B) = \sigma_{33}(A)\delta^2 \ . \qquad (2.6)
$$

Then the bending-plane beam emittance at the exit is

beam emittance growth and to decouple the high-pass accelerated beams with the injected beams from that 180 degree bend. Fig. 3 is a staircase-line consisting of 7 quads and 4 parallel dipoles, and Fig. 4 is a slide-line consisting of 4 quads and 3 sector dipoles.
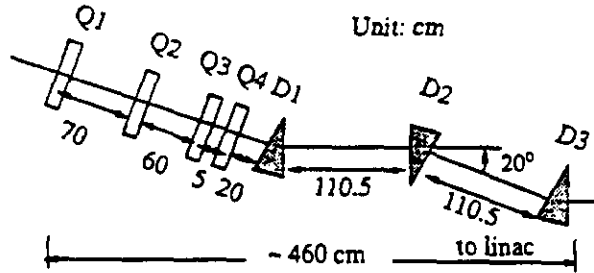


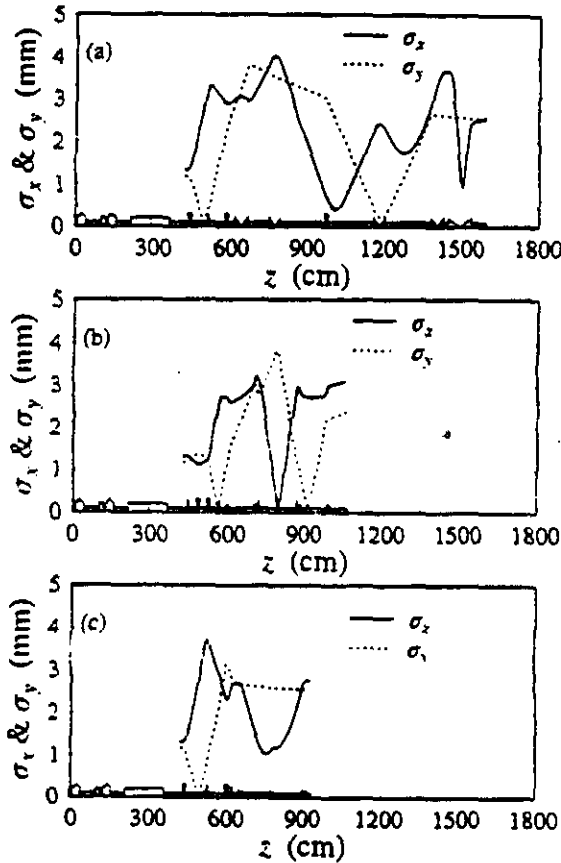Fig. 4 A slide injection line ($R_{56} = -0.138$ m).



Fig. 5 Beam envelope evolution in three injection lines: (a) 180°-bend; (b) staircase; (c) slide.

Table 1 shows the performance comparisons among these three designs. The numbers in the table are the beam parameters at the end of each injection beam line.

Table 1 Performance comparisons among three designs

| Beam parameters | 180°-bend | staircase | slide |
|---|---|---|---|
| $\varepsilon_{nrms}$ ($\pi$ mm mrad) | 8 | 6.8 | 4.6 |
| $\varepsilon_{\phi rms}$ ($\pi$ keV-deg) | 27 | 19 | 15 |
| $4\sigma_t$ (ps) | 11 | 10 | 4 |

The simulations started from the cathode with a 135 pCcharge/bunch, and continued to the cryounit exit. with theintermediate results saved. Then we restarted the simulation by incorporating each injection line with the preceding part. The restarted beam parameters are: transverse normalized emittance $\varepsilon_{nrms} = 4.2\,\pi$ mm mrad, longitudinal emittance $\varepsilon_{\phi rms} = 11.6\,\pi$ keV-deg, and bunch length $4\sigma_t = 6.7$ ps.

Fig. 5 shows the beam envelope evolution along these lines. It is seen that the beam's betatron-oscillation becomes more and more regular, and the number of crossovers (very small beam waists) becomes smaller and smaller, from the 180°-bend-line to the slide-line. Due to its simplicity and better performance, the slide-design is chosen as the nominal injection beam line for the CEBAF FEL injector.

As is seen from Fig. 5 (c), the 4 quads before the three sector dipoles in the slide-line constitute a telescopic lens which can variably magnify the beam's β-functions from the cryounit exit to the entrance of the first dipole. The 3-magnet bending system preserves the beam's parallelness in both x- and y-plane [13, 14] while transporting the beam to the main accelerator. Betatron-function magnification and beam deflection are thus decoupled, which will greatly ease the operation.

Finally, we note that this 3-magnet bending system is non-isochronous with $R_{56} = \rho(3\alpha - 4\sin\alpha)$, where $\rho$ and $\alpha$ are the bending radius and angle of each dipole. The achromaticity condition is $L/\rho = \cot\alpha - \tan(\alpha/2)$, where $L$ is the edge-to-edge distance between the two adjacent dipoles. The dispersion at the symmetry plane is
$$\eta_c = \rho(2\cos(\alpha/2) - 1), \quad \text{and the focal length is}$$
$f_x = \rho/2\sin(\alpha/2)$. For small $\alpha$'s, we have $\eta_c/f_x = \alpha$. which reduces Eq. (5) to Eq. (11) of [9].

## VI. REFERENCES

[1] D. Neuffer et al., these proceedings.
[2] F. Dylla et al., these proceedings.
[3] H. Liu et al., these proceedings.
[4] H. Liu et al., Nucl. Instr. Meth. A358 (1995) 475.
[5] B. Carlsten et al., Nucl. Instr. Meth. A296 (1992) 687.
[6] D. Douglas, private communication.
[7] R. Rand, Recirculating Electron Accelerators, (Harwood Academic Publishers, New York, 1984).
[8] H. Enge, Rev. Sci. Instrum., 34 (1963) 385.
[9] B. Carlsten et al., Phys. Rev. E. 51 (1995) 1453.
[10] A. Banford, The Transport of Charged Particle Beams, London, E. & F. N. Spon Limited, 1966.
[11] H. Liu, CEBAF TN# 95-004.
[12] T. Raubenheimer, Workshop on 4th Generation Light Sources, SSRL, (1992) 263.
[13] S. Penner, Rev. Sci. Instrum., 32, 150 (1961).
[14] B. Milman, Nucl. Instrum. Methods, 20 (1963), p.13.